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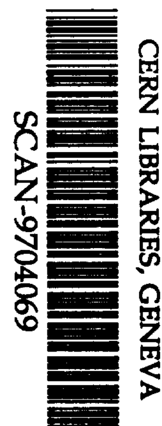
Amorphous Silicon/Crystalline Silicon Heterojunctions for Nuclear Radiation Detector Applications



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Amorphous Silicon/Crystalline Silicon Heterojunctions for Nuclear Radiation Detector Applications

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Abstract

Results on the characterization of the electrical properties of amorphous silicon films for the three different growth methods, RF sputtering, PECVD, and LPCVD are reported. The performance of these a-Si films as heterojunctions on high resistivity p-type and n-type crystalline silicon is examined by measuring the noise, leakage current and the alpha particle response of 5 mm diameter detector structures. It is demonstrated that heterojunction detectors formed by RF sputtered films and PECVD films are comparable in performance with conventional surface barrier detectors. The results indicate that the a-Si/c-Si heterojunctions have the potential to greatly simplify detector fabrication. Directions for future avenues of nuclear particle detector development are indicated.

I. Introduction

Recently reported work on amorphous silicon/crystalline silicon, a-Si/c-Si, heterojunctions[1] plus our own experience with amorphous semiconductor contacts for Si and Ge radiation detectors[2] suggested that a significant simplification of silicon detector technology could be realized by replacing conventional contacts with heterojunctions.

The principal contact technologies presently used in the fabrication of silicon detectors are either surface barrier or diffused/implanted p-n junctions. Both of these technologies have limitations. The surface barrier technology results in contacts that are extremely fragile. The diffused/implanted junction technology requires high process temperatures that can degrade the carrier generation lifetime in high purity silicon. A-Si/c-Si heterojunctions offer a novel alternative. These heterojunctions can exhibit nearly ideal p-n junction performance and can be grown at very low temperatures[3]. Surprisingly, while amorphous silicon has been studied as a radiation detector material because of its radiation hardness and large-area capability[4], there has been only a very limited amount of work on detector structures based on the a- Si/c-Si system[5].

In the following, we discuss our results on a-Si/c-Si heterojunctions formed via three different deposition techniques: RF sputter deposition, plasma enhanced chemical vapor deposition (PECVD), and low pressure chemical vapor deposition (LPCVD). RF sputter deposition has been used successfully at LBNL to fabricate a-Ge/c-Ge and a-Si/c-Si heterojunction detectors. PECVD, the standard method used to grow solar cells and thin film transistors, has been used to fabricate segmented radiation detectors on high purity crystalline silicon[6]. LPCVD is commonly used to grow the amorphous silicon that serves as the precursor stage for polycrystalline silicon growth. In addition, the different process temperatures required for RF sputtering (room temperature), PECVD (~200-250°C) and LPCVD (~600°C) may have varying effects on the surface electronic properties of a high resistivity c-Si substrate. These three a-Si film growth techniques span a wide range in deposition temperatures and produce films with distinctly different electronic properties, which are discussed further below.

II. A-Si Film Characteristics

To characterize the a-Si films, we deposited the films onto glass substrates using each of the three deposition techniques. The deposition conditions were as follows. The RF sputtered films were grown at room temperature with an RF power of 400 W, a pressure of 7.0 mTorr and in ambients of pure Ar or Ar with 17.5% H_2. The PECVD depositions were carried out with a substrate temperature of 190°C, an RF power of 5-7 W, a pressure of 0.3 Torr and a flow of 40 sccm SiH_4 (undoped film), with the addition of 7.6 sccm 1% Phosphine in Silane (phosphorus-doped, N-type film) or 15.2 sccm 0.5 % Diborane in Helium (boron-doped, P-type film). The LPCVD films were deposited in a furnace at 590°C, a pressure of ~50 Torr, and with a SiH_4 flow of 20 sccm. The deposition times with each technique were selected to produce an a-Si film thickness of ~200 nm.

Coplanar Cr/Au contacts 10 mm long and 1.0 mm apart were then evaporated onto the a-Si films to allow measurement of the film resistivity. From these measurements, we obtained information on the film conductivity dependence on deposition process, doping effects and dominant conduction mechanism. As expected, the three deposition techniques yielded films with distinctly different electronic conductivity.

Our conductivity versus temperature data for the RF sputtered films (both in pure Ar and with 17.5% H_2) and the LPCVD film are better fitted with a $1/T^{1/4}$ dependence than a $1/T$ dependence, which is characteristic of an activation energy type conductance. This indicates that the RF sputtered films

and possibly the LPCVD film conduct via hopping, which is characteristic of highly disordered films with high defect densities ($\sim 1 \times 10^{18}$ /cm^3). The PECVD grown films appear to conduct via an activation type mechanism, which is characteristic of longer range ordered films with lower defect densities ($\sim 1 \times 10^{15}$/cm^3). Table 1 contains a listing of the parameters used to fit the conductivity data.

Table 1. Summary of a-Si Conductivity Measurements

No.	Deposition Process	Constant	Value	Conductivity (300 K) Ω^{-1}-cm^{-1}
1	Sputter-Argon	σ_o (Ω^{-1}-cm^{-1})	5.02×10^{4}	1.5×10^{-6}
		A ($K^{1/4}$)	98.7	
2	Sputter-Argon+H_2	σ_o (Ω^{-1}-cm^{-1})	1.0×10^{29}	5.4×10^{-11}
		A ($K^{1/4}$)	377.2	
3	PECVD-undoped	σ_o (Ω^{-1}-cm^{-1})	15.31	1.4×10^{-7}
		E_A (eV)	0.642	
4	PECVD-boron	σ_o (Ω^{-1}-cm^{-1})	0.379	2.0×10^{-6}
		E_A (eV)	0.304	
5	PECVD-Phosphorus	σ_o (Ω^{-1}-cm^{-1})	11.9×10^{3}	3.0×10^{-4}
		E_A (eV)	0.518	
6	LPCVD-undoped	σ_o (Ω^{-1}-cm^{-1})	3×10^{24}	5.2×10^{-8}
		A ($K^{1/4}$)	303.3	

Table Notes:

a) Samples 1, 2, and 6 we assume conduct via hopping; the conductivity is then modeled by: $\sigma = \sigma_o \exp(-A/T^{1/4})$.

b) Samples 3, 4, and 5, we assume conduct via an activation energy; the conductivity is then modeled by: $\sigma = \sigma_o \exp(-E_A/kT)$.

The results in Table 1 confirm that the three deposition techniques yielded a-Si films with substantially different electronic characteristics. Much of the recent emphasis in a-Si film development has been on improving the film transport properties. But, as discussed in Section V below, the a-Si film transport properties do not appear to be important in a-Si/c-Si contact formation for silicon radiation detector technology.

III. Test Diodes

Using the same deposition conditions as employed with the glass substrates, we also deposited ~200 nm thick a-Si films onto high resistivity p-type (1,000 and 5,000 Ω-cm) and n-type (5,000 Ω-cm) 375 μm thick silicon wafers (one side polished; 1% HF dip and H_2O rinse before deposition). Onto these deposited films we then evaporated metals (Al or Cr/Au) to form the a-Si/c-Si heterojunction contact structure, which is shown schematically in Figure 1. Ohmic contacts, p^+ or n^+, were implanted into the substrates prior to the a-Si film depositions. These contacts ensured that only the a-Si heterojunction blocking characteristics would be measured in our subsequent tests.

To determine whether photolithographic processes (positive photoresist) have any detrimental effect on the a-Si/c-Si heterojunction properties, we formed the metal contacts on the test samples both with an evaporation mask and with a photolithographic process. For most of the samples prepared, we fabricated at least nine 5 mm diameter diodes.

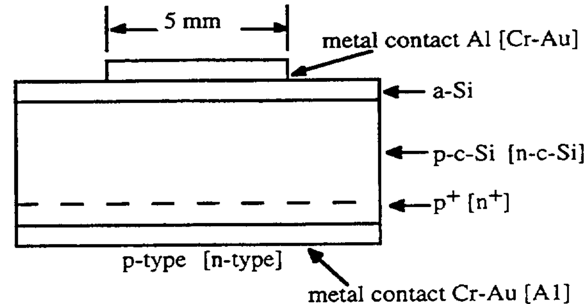

Figure 1. Cross-section of the p-type and [n-type] a-Si heterojunction detectors. The active area of the detector is defined by the 5 mm diameter metal evaporation on the 200 nm thick a-Si film. The n-type device metals etc. are noted in [ ] in the figure. The p^+ [n^+] ohmic contact was formed by boron [phosphorus] ion implantation, 50 keV, 2×10^{15} ions/cm^2 and annealed at 800 °C for 30 minutes prior to the a-Si film deposition.

IV. Diode Results

We first checked each of the heterojunction-based diodes by measuring their leakage current and noise as a function of reverse bias voltage at room temperature. Since the devices fabricated are, in fact, partially depleted charged particle detectors, our procedures followed ANSI/IEEE Std. 300-1988[7]. Our average values from these measurements are summarized in Table 2, while a representative ^{241}Am alpha spectrum is shown in Figure 2. There was no appreciable difference in the heterojunction diodes formed by evaporation through a metal mask and those with the metal contacts formed by photoresist patterning. The values in the table are, therefore, averaged over both sets, typically a total of 18 diodes. From these results, it can be seen that the a-Si heterojunctions formed by RF sputtering in Ar yielded the best diode performance on p-type substrates, while diborane-doped PECVD yielded the best diode performance on n-type.

V. Discussion

Table 3 summarizes our assessment of the a-Si/c-Si heterojunction properties at room temperature of the various a-Si film depositions that we performed on three different silicon substrates. While not denoted as such in Table 2 or 3, the RF sputtered films are "undoped" in that phosphorus or boron dopants have not been added to alter the film conductivity, as has been demonstrated by Paul et. al. [8].

Table 2. Summary of ^{241}Am alpha measurements

Process	P-type, 1,000 Ω-cm				P-type, 5,000 Ω-cm				N-type, 5,000 Ω-cm			
	Bias V	I μA	ΔE_α keV	ΔE_p keV	Bias V	I μA	ΔE_α keV	ΔE_p keV	Bias V	I μA	ΔE_α keV	ΔE_p keV
RF Argon	60	0.68	31.3	11.9	80	0.70	27.0	8.6	30	1.50	35.7	27.0
RF Argon + H_2	60	3.20	30.3	19.5	90	0.60	31.4	8.6	14	0.41	47.6	34.6
PECVD-undoped	60	4.80	27.0	18.4	90	0.86	33.5	21.6	leaky	leaky	leaky	leaky
PECVD-boron	---	---	---	---	---	---	---	---	20	0.16	24.9	10.8
PECVD-phosphorus	60	0.72	32.2	12.2	80	0.77	31.3	10.2	---	---	---	---
LPCVD-undoped	60	2.80	35.6	32.4	90	10.0	34.6	24.8	leaky	leaky	leaky	leaky

Table Notes:

a) The measurements were performed with an amplifier peaking time of 0.8 μsec.

b) ΔE_α and ΔE_p are the Full Width Half Maximum (FWHM) values for the ^{241}Am alpha peak and electronic pulser respectively.

c) The table entries noted " ---" were not fabricated as these a-Si/c-Si structures were not expected to form blocking contacts.

d) The table entries noted "leaky" had reverse leakage currents greater than 10μA with 10 V reverse bias.

Table 3. Characterization of heterojunctions formed

Process	P-type, 1000 Ω-cm	P-type, 5000 Ω-cm	N-type, 5000 Ω-cm
RF Argon	n^+	n^+	p
RF Argon + H_2	n	n^+	p
PECVD-undoped	n	n^+	n
PECVD-boron	---	---	p^+
PECVD-phosphorus	n^+	n^+	---
LPCVD-undoped	n	n	n

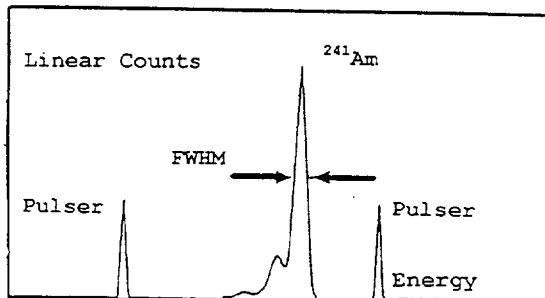

Figure 2. The ^{241}Am alpha spectrum produced by a 5 mm diameter a-Si/c-Si heterojunction produced by RF sputtering in Argon. The contact metal is Al.

It is interesting to note the similarities in behavior of the a-Si/c-Si contacts on high resistivity silicon with a-Ge/c-Ge contacts on high purity germanium. Our previous investigation of sputtered a-Ge/c-Ge heterojunctions has shown that the a-Ge contacts functioned as blocking contacts under either polarity of applied bias. The sputtered a-Ge/c-Ge contacts however exhibited better blocking properties when used as n-type contacts than as p-type contacts [9]. Also, the hydrogen concentration of the sputter gas used in the deposition process affected the electrical properties of the contacts. Higher hydrogen concentrations resulted in higher barrier heights for hole injection and lower barrier heights for electron injection, thus resulting in a more n-type behavior.

The a-Si/c-Si junctions also showed similar bipolar blocking properties, i.e., diode behavior was obtained both for n-type and p-type materials. And like germanium, the sputtered a-Si/c-Si contacts performed better as n-type than as p-type contacts, although the presence of hydrogen does not appear to influence junction properties as much as with germanium. However, the present device structure, with the a-Si as the blocking contact, does not allow the ready measurement of the barrier height as was done on germanium, where the a-Ge heterojunction acted as an ohmic contact. Therefore, no definite conclusion can be drawn at the present time regarding the effect of hydrogen and different deposition processes on the blocking properties of the contacts.

Comparison of the performance of the RF sputtered and the phosphorus-doped PECVD deposited contacts on the p-type substrates suggests that the a-Si film quality is not important to a-Si/c-Si heterojunction leakage currents. As noted earlier in the discussion on film conductivity, the RF sputtered films appear to have high defect densities, while the PECVD films appear to have lower defect densities. Yet, from the results in Table 2, the RF sputtered contact yielded slightly lower leakage currents than the PECVD grown films. But the results here may be misleading, as in both instances the a-Si films are also acting as passivating layers at the heterojunction edge, and the diode leakage currents are possibly dominated by this peripheral "surface" current arising partially from the conductivity of the a-Si films. We have further tests planned to explore the sources of the diode leakage current.

conductivity of the a-Si films. We have further tests planned to explore the sources of the diode leakage current.

The "undoped" films produced by PECVD and LPCVD did not, with the exception of the PECVD deposition on the 5000 Ω-cm sample, yield low leakage junctions. While both the boron-doped and phosphorus-doped PECVD films produced low leakage current diodes, we did not have the capability of producing similarly doped films with LPCVD. Therefore we cannot now make an assessment as to whether doped LPCVD films have application in detector fabrication.

A figure of merit against which to compare these a-Si/c-Si heterojunction leakage currents is the 1nA/1cm^2/100 μm (reverse leakage current/device area/depletion depth) commonly quoted for oxide-passivated silicon planar technology devices[10]. For the a-Si/c-Si heterojunctions fabricated here, this figure of merit is ~ 0.5-2.0 μA/1cm^2/100 μm, comparable to values we have obtained with silicon surface barrier technology.

While our present heterojunction performance falls short of that attained by oxide-passivated devices, this heterojunction technology does open the possibility of fabricating novel Si detectors such as thick (>1 mm) segmented Si detectors and Si x-ray detectors. Thick Si detectors and Si x-ray detectors are normally fabricated via lithium-ion compensation, a process that is incompatible with high processing temperatures[11]. We have already successfully fabricated thick Si(Li) segmented and Si(Li) x-ray detectors with heterojunctions. In particular a "normal" Si(Li) x-ray detector with an entrance contact composed of aluminum and RF sputtered (Ar + 17.5% H_2) a-Si had photopeak/background performance equivalent to that reported earlier on an "inverted" Si(Li) diode structure[12].

VI. Conclusions

With these results we have shown that contacts can be formed by RF sputtering or PECVD. In particular:

- Both "undoped" RF sputtered films and phosphorous-doped PECVD films form blocking contacts on p-type silicon that have low leakage currents and low noise.
- Only boron-doped PECVD films form blocking contacts on n-type silicon that also have low leakage currents and low noise.
- Both RF sputtered films and PECVD deposited films also act as passivating layers. The leakage currents on the test structures have been stable with time, and the behavior of these devices has been similar to the surface barrier detectors now commonly used.

VII. Acknowledgments

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